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The effects of building-related factors on classroom relative humidity among North Carolina schools participating in the "Free to Breathe, Free to Teach" study

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Abstract

Both high and low indoor relative humidity (RH) directly impact indoor air quality (IAQ), an important school health concern. Prior school studies reported a high prevalence of mold, roaches, and water damage; however, few examined associations between modifiable classroom factors and RH, a quantitative indicator of dampness. We recorded RH longitudinally in 134 North Carolina classrooms (n= 9066 classroom-days) to quantify the relationships between modifiable classroom factors and average daily RH below, within, or above levels recommended to improve school IAQ (30–50% or 30–60% RH). The odds of having high RH (>60%) were 5.8 (95% Confidence Interval (CI): 2.9, 11.3) times higher in classrooms with annual compared to quarterly heating, ventilating, and air conditioning (HVAC) system maintenance, and 2.5 (95% CI: 1.5, 4.2) times higher in classrooms with HVAC economizers compared to those without economizers. Classrooms with direct expansion split systems compared to chilled water systems had 2.7 (95% CI: 1.7, 4.4) times higher odds of low RH (<30%). When unoccupied, classrooms with thermostat

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Supporting Information
Additional supporting information may be found in the online version of this article:
Supplemental Materials: Equations
Equation S1: Conversion from temperature (°C) to saturation vapor pressure (kPa)
Equation S2: Unit conversion of saturation vapor pressure from kPa to in Hg
Equation S3: Conversion from saturation vapor pressure values (in Hg) to vapor pressure (in Hg)
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Supplemental Materials: Tables
Table S1: Univariate associations between other building-related factors and daily average relative humidity (RH).
Table S2: Full model for association between water damage and daily average RH level.
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Table S4: Full model for association between presence of an economizer and daily average RH level.
Table S5: Full model for association between heating/ cooling mechanism and daily average RH level.
Table S6: Joint effects of visible classroom water damage and dehumidifier use on daily average RH.

setbacks had 3.7 (95% CI: 1.7, 8.3) times the odds of high RH (>60%) of those without setbacks. This research suggests actionable decision points for school design and maintenance to prevent high or low classroom RH.

Keywords

Indoor air quality; Relative humidity; Schools; Classrooms; Building-related factors; Longitudinal study

Introduction

The warm, humid climate of the southeastern United States (US) presents challenges to maintaining indoor air quality (IAQ) in school buildings. In the past decade, school employees reported evidence of flooding (35%), visible mold (49%), roaches (78%), rodents (73%), and moldy odors (73%) in North Carolina (NC) public schools (Mirabelli et al., 2006). These findings were suggestive of excessive indoor humidity. Such reports are concerning, because studies of populations living in homes and attending schools with excessive dampness concluded that damp environments are hazardous to the respiratory health of occupants (Borras-Santos et al., 2013; Haverinen-Shaughnessy et al., 2004; Jaakkola et al., 2010; Norback et al., 2011).

To date, studies of indoor dampness in schools have been largely based on visual inspections and mold tests. Relative humidity (RH), the fraction of water vapor in the air at a given temperature relative to the temperature-dependent capacity of the air for water vapor, can be recorded using simple, low cost technology (Jaakkola, 2006). In addition, schools have already been given specific recommendations for RH. The US Environmental Protection Agency's (EPA) "Indoor Air Quality: Tools for Schools" recommended that schools should keep indoor RH levels between 30–50%, or at minimum, under 60% RH to control mold, dust mites, and pests and provide comfortable conditions for building occupants (United States Environmental Protection Agency, 1995; United States Environmental Protection Agency, 2008; United States Environmental Protection Agency, 2009). Maintaining a typical daily average of ≤60% RH may be sufficient for controlling mold growth on building materials; however, may not be sufficiently low enough to control dust mites (Arlian et al., 1998; Arlian et al., 2002; Johansson et al., 2013a; Johansson et al., 2013b). The current study uses RH as a quantitative indicator of the potential for dampness and identifies structural and mechanical conditions related to poor control of RH in NC classrooms, examining both possible cut points for high RH.

Several factors are expected to affect RH control in schools. Outdoor humidity and temperature, which vary by season and geography, affect indoor humidity when outdoor air moves in through openings in the building envelope via low pressure caused by warm air moving upward, also known as the "stack effect" (JLC Field Guide to Residential Construction: A Manual of Best Practice, 2006; Brumbaugh, 2004). While outdoor humidity and temperature are outside of the control of school facilities maintenance personnel, there are several, modifiable building-related factors that may influence indoor RH. These factors include unintended air flow, the quality and frequency of maintenance, and the type and quality of insulation, building materials, and air seals (Persily, 1999).

Another structural factor which may affect classroom humidity is the operation, maintenance, and choice of heating, ventilating, and air conditioning (HVAC) systems. Most school air conditioning systems are not designed specifically to control humidity, but some can remove moisture from the air during the cooling process (Brumbaugh, 2004; Cooper, 1998). All HVAC units have fans that supply outdoor air to keep indoor carbon dioxide and odor levels low. The fans come on when scheduled to continuously to supply the classrooms with outdoor air changes, but this process introduces moist air into the classrooms. A study of school HVAC systems with versus without active humidity control found that those with humidity control intended by design could maintain lower humidity while still meeting ventilation requirements. However, those without active humidity control could not meet both ventilation and humidity recommendations simultaneously (Bayer et al., 2002).

The aim of this research was to identify factors associated with poorly controlled humidity in schools. We examined the association between classroom RH outside of the two recommended (30–50%; 30–60%) ranges and modifiable factors such as school mechanical, ventilation and maintenance practices, and previous water damage.

Materials and Methods

This research was part of a longitudinal cohort study of classroom IAQ factors conducted during the 2010–2011 academic year. School district maintenance personnel in two NC school districts recruited principals from 10 public schools, elementary through high school, and acquired permission for their employees to participate in this study. Within these schools, we invited all full-time teachers have their classrooms inspected and monitored.

Building-Related Factors and Climate Control

At the start of follow-up, a team of trained individuals inspected 233 rooms (including classrooms, common areas, and offices) according to the EPA’s IAQ Tools for Schools Walkthrough Inspection procedures (United States Environmental Protection Agency, 1995). Portable monitors recorded carbon dioxide, carbon monoxide, RH, and temperature. During these inspections, the study team noted potential asthma triggers and building-related factors using a checklist based on the Tools for Schools Walkthrough Inspection Checklist.

Water damage was assessed based on signs of current or recent damage such as rust, mold, or water spots. The researchers created a dichotomous variable defining water damage as “1” for a given classroom if any of the following issues were noted during the walkthrough inspection: any leaks; recent history of flooding within the past 5 years; any visible signs of moisture/ water damage; any visible signs of mold/ mildew growth.

During the walkthrough inspection, the researchers asked district maintenance experts about HVAC maintenance schedules and building age. HVAC maintenance schedule was defined for each classroom as a three level variable: maintained as needed, quarterly maintenance, or annual maintenance. The researchers calculated building age by subtracting the year of building completion from the year of data collection. For analysis, building age was categorized as 0–10, 11–20, 31–40, or >40 years old. There were no buildings in our study in the 21–30 year-old age category.

At the end of the study, we surveyed a maintenance expert from each school district to collect information about the type, operation, and design features of HVAC systems in school buildings, building wings or classrooms, and portable classrooms occupied by study participants. We asked about use of an economizer, a mechanical device used for energy efficiency. An economizer draws outdoor air into the building for cooling and ventilation. In humid climates, this may lead to increased indoor RH when the outdoor air supply is not dehumidified before being circulated. Certain types of economizers use enthalpy controls which prevent cool, extremely humid air from being drawn into the building; however, in our study, the HVAC systems with economizers used temperature or timed controls to vary the air intake.

Another method of energy conservation explored in this study was programming thermostats to perform setbacks, which is when the temperature set point on the thermostat is changed during unoccupied times. We expected setbacks to reduce indoor RH during unoccupied times, because the fans that bring in outside air should run less often. Since the units are set to run at a higher temperature during the cooling season and lower temperature during the heating season, the fan should only operate when the room gets to the unoccupied set point. Reduced fan operation consequently lowers the ventilation rates during unoccupied hours. Presence of programmed setbacks, defined by whether or not there was a different thermostat set point for unoccupied vs. occupied times, were noted for each classroom (for those with individual HVAC systems), building wing, or school building.

The HVAC systems in the participating schools all used one of the following heating/ cooling mechanisms: chilled water, heat pump/ refrigerant or direct expansion (Dx) split system. Chilled water systems use air-cooled chillers to chill water. The building contains a continuous water loop that is connected both to the chiller and the associated air handler for cooling. When there is a need for cooling, the chilled water valve opens on the air handler, which starts the pump on the chilled water loop. The chiller will detect the flow of water and begin cooling the water down to a set temperature. Before being circulated in the room, the supply air is cooled by being passed over the chilled water loop. Heat pump with refrigerant systems and Dx split systems both use refrigerant to directly cool the surrounding air. Heat pumps with refrigerant have valves that reverse the flow of refrigerant to work for cooling or heating. Dx split systems use refrigerant for cooling only and provide heat from electric heat strips or hot water heating coils supplied by boilers. Both Dx split systems and chilled water systems may have indoor and outdoor components and are generally found in newer buildings; whereas, heat pumps with refrigerant cooling systems are typically self-contained units found in older buildings.

In our study, two, new, single-building schools had HVAC systems with energy recovery units (ERU) connected to the air handlers that supplied the classrooms. The ERUs were equipped with desiccant- containing enthalpy wheels and transfer sensible heat and moisture between the incoming outdoor air and the exhausted indoor air. During the warmer months, these enthalpy wheels dehumidify hot and humid incoming outdoor air, by transferring moisture from the outdoor air to the exhausted air. However, during cold weather when the outdoor air is dry, the incoming outdoor air can be humidified by transfer of moisture from exhaust air to incoming outdoor air. Thus, enthalpy wheels may prevent high indoor humidity during warm, humid weather and low indoor humidity during periods of cold, dry weather. The two schools will be referred to as having “enthalpy wheels for dehumidification” for the purposes of this analysis.

In one of the schools with enthalpy wheels for dehumidification, the classrooms were cooled using a chilled water cooling mechanism. Three rooms (gym, cafeteria, and auditorium) were on direct digital controls (DDC) with an adjustable humidity set point (55% RH) and the ability to reduce the humidity to within 5% of the set point. The units had a pre-heat coil for heating during the winter, a cooling coil, and a reheat coil for dehumidification. When the humidity got above 55%, the cooling and reheat coils opened to maintain the discharge air set point and removed the moisture from the recirculated air. In the other school with enthalpy wheels for dehumidification, classroom units had refrigerant-based cooling and water source heat pumps equipped with hot gas reheat for dehumidification. Cooling was the priority for these units, so the dehumidification of recirculated air did not start until the cooling need was satisfied.

Prospective Data Collection

During follow-up, Extech data logging hygrometers (Model 42270, Extech Instruments Corporation, Nashua, NH) recorded temperature and RH in 134 classrooms at 15 minute intervals. The researchers placed hygrometers within the participants’ usual breathing zones, at a location in the classroom where the participant spent most of her time on a typical day. The factory specifications for these instruments were ±0.6°C accuracy for normal temperature conditions (−20 to 50 °C) and ±3% accuracy for RH (0 to 100%). Hygrometers were tested for accuracy and precision before and during data collection, by comparison to sling psychrometer measurements and data collected while co-locating hygrometers in both indoor (controlled) and outdoor (uncontrolled) environments (Gaetz, 2014).

We collected data in two phases (Phase 1: October 20 to December 10, 2010; Phase 2: February 6 to June 13, 2011) and monitored each classroom for 4–12 weeks. We measured temperature and RH in each classroom during at least two indoor climate seasons: heating, cooling, and/ or transition. Indoor classroom RH observations were summarized as daily means. The outcome, daily mean RH, was categorized as below (<30%), above (>50%), or within the recommended RH level 1 (30–50%) and below (<30%), above (>60%), or within the currently recommended RH level 2 (30–60%) (United States Environmental Protection Agency, 2009; United States Environmental Protection Agency, 1995).

We defined building occupancy based on the published school schedule for the 2010–2011 school year. School buildings were defined as unoccupied during the weekend and scheduled holidays and occupied during each weekday, from one hour before the school day began to one hour after school ended (i.e. 7am–4pm in a school scheduled to start at 8am and end at 3pm). In a separate analysis, daily RH was averaged separately for occupied vs.

unoccupied times for each classroom to compare differences in estimates after stratification by occupancy.

The NC State Climate Office (SCO) provided daily averages of outdoor RH and temperatures measured by the weather station closest to each study site, corresponding to each day of indoor RH and temperature measurement (State Climate Office of North Carolina, 2010). The NC SCO also provided equations for converting outdoor and indoor RH measurements into absolute humidity for a comparison that is independent of temperature (Parish and Putnam, 1977; Snyder, 2005). See Supplemental Materials for equations used to convert temperature and RH measurements to absolute humidity (Equations S1-S4).

School buildings in the Southeast typically have year-round indoor temperature control, with a "cooling season" during the warmer months and a "heating season" during the colder months. Mild temperatures between seasons can lead to transition periods, during which the HVAC system's compressor or heat exchange may not run for long enough to dehumidify the outdoor air. Thus, the researchers categorized each day as a heating, cooling, or transition day, using daily average outdoor temperatures to predict when heating or cooling would have been requested in mechanically ventilated buildings. The following categories were created based on standards for a naturally ventilated building: heating days= outdoor temperature less than 15°C, transition days= 15–23°C, cooling days= more than 23 °C (Brager and de Dear, 2001).

Statistical Methods

The hygrometer data consisted of 852,519 RH measurements. These were summarized into 9066 values representing the average daily RH in the 134 study classrooms over the study period. Letting *i* denote classroom, and *t* denote day, the outcome variable Y_{it} is a variable denoting the average RH in classroom *i* over day *t*. We coded Y_{it} with a value of "3" if the average RH for classroom *i* on day *t* was >50% or >60%, a value of "2" if the average RH for classroom *i* on day *t* was <30%, and a value "1" if the average RH was within the referent ranges (30–50%; 30–60%). The researchers compared nominal categories, 3 to 1 and 2 to 1.

The SURVEYLOGISTIC procedure (SAS software, Version 9.3) was used to estimate generalized logits (g-logit link, multinomial distribution) (Equation 1) for a nominal polytomous outcome Y_{it} defined above, accounting for repeated measures by classroom using the Taylor series method for variance estimation. Multivariate models were fit with potential confounders and effect measure modifiers chosen *a priori*.

$$\log\left[\frac{\Pr(\mathrm{Y}it=\mathrm{g}|\mathrm{x})}{\Pr(\mathrm{Y}it=1|\mathrm{x})}\right]=\hat{\beta}_{0\mathrm{g}}+\hat{\beta}_{1\mathrm{g}}\mathrm{x}_{1\mathrm{it}}+\hat{\beta}_{\mathrm{ng}}\mathrm{z}_{\mathrm{nit}}+\gamma_{\mathrm{ng}}\mathrm{x}_{1\mathrm{it}}\mathrm{z}_{\mathrm{nit}} \quad \text{(Equation 1)}$$

where g= outcomes 2 or 3; x=observed main exposure, z= observed covariate, n=number of covariates, t=time(days), i= classroom, $\hat{\beta}_n$ =slope of covariate, and γ = slope of product term

Each main exposure (building-related factor) of interest had a different set of *a priori* confounders and effect measure modifiers, chosen based on expected relationships between the main exposure and other important variables. Effect measure modification between visible water damage and classroom dehumidifier use was estimated by entering a product term for the interaction between these two variables into the full model. Dehumidifier use was expected to be caused by visible water damage and to affect classroom RH. The effect of water damage was adjusted for the potential confounders-- heating/ cooling mechanism, outdoor RH, and building age—in the full model with and without the product term. Building age is likely to be a determinant of the air exchange rate standard that the building and its components were designed to achieve (Janssen, 1999). Depending on its age and design, some cooling equipment is more prone to leaking than others and thus may be more likely to cause water damage. Thus, building age was used as a proxy for unmeasured HVAC age. For these reasons, models for frequency of HVAC system maintenance and heating/ cooling mechanism also included building age as a potential confounder. The effect of heating/ cooling mechanism was also adjusted for heating/cooling season since the cooling mode was not likely to be used during the heating season except to remove moisture before the air is reheated. The effect of having an economizer on indoor RH was adjusted for presence of enthalpy wheels for dehumidification of outdoor air. Adjustment for this variable also controls for the effect of outdoor RH, so we did not need to enter outdoor RH into the model.

To model the effect of thermostat setbacks on RH stratified by building occupancy, RH observations were averaged separately for times when the buildings were occupied versus unoccupied. We modeled data from 14952 classroom observations from each combination of classroom, day, and building occupancy (yes/no). Stratified average classroom RH was then categorized into high (>50%; >60%), low (<30%), and recommended RH (30–50%; 30–60%).

Results

Out of 9066 classroom-days monitored, 5905 classroom-days had scheduled building occupancy. An average daily RH value could not be derived for 22 classroom-days (0.2%) with missing RH data. Classrooms were monitored during the school year (October to June) for a range of 28 to 84 days. Average indoor RH was similar for unoccupied (mean= 42.8%; standard deviation (SD) =12.3) and occupied times (mean= 42.4%; SD=13.0). Average indoor daily RH was higher during cooling (mean=51.9%; SD =10.2) and transition days (mean =48.7%; SD=8.8) than heating days (mean =33.0%; SD=9.0) and lower in autumn (mean=35.8%; SD=13.4) and winter (mean=33.7%; SD=7.6) compared to spring (mean=47.4%; SD= 10.5).

Within schools, fluctuations in indoor RH followed daily trends in outdoor temperature more closely than trends in indoor temperature, which stayed fairly constant over time, or outdoor RH. Overall, the Coastal school district had a higher and less variable average outdoor RH, temperature, and absolute humidity (AH) compared to the Piedmont district (Table 1). Indoor RH and AH were slightly higher and more variable in the Piedmont than Coastal district.

Several schools were not able to maintain the more conservative RH levels (30–50%) in monitored classrooms for more than half of the follow-up period. One school (which provided information on 12 classrooms over 65 days) had RH outside of this range on most (89%) of the classroom-days monitored. The highest proportion of classroom-days within RH level 1 (30–50%) occurred during the transitional periods of HVAC operation. For example in November, between 60–87% of classroom-days were within this RH level. By comparison in December, the same schools had only 6–39% of classroom-days within this RH level.

The odds of high indoor RH increased as outdoor humidity increased. This association was stronger during occupied [$OR_{10\%\text{ increase in outdoor RH}}$= 1.70 (1.57, 1.83)] than unoccupied times [$OR_{10\%\text{ increase in outdoor RH}}$ = 1.49 (1.43, 1.55)]. The building-related factors associated with an increased odds of high indoor RH included having less frequently scheduled HVAC maintenance and presence of an economizer, for both RH cut points (>50% and >60%) (Table 2). However, water damage in the classroom at the time of the inspection was not associated with high RH. Having a direct-expansion split system was associated with an increased odds of low classroom RH (<30%) compared to having a chilled water heating/ cooling mechanism (Table 3).

After stratification by building occupancy, the estimates for the associations between building-related factors and daily RH were similar in direction and magnitude to the un-stratified estimates shown in Tables 2 and 3. For most models, estimates for unoccupied times were almost identical to un-stratified estimates, though estimates for occupied times were generally further from the null and less precise. However, the association between high RH (>50%) and programmed setbacks was stronger for unoccupied [$OR_{\text{setbacks, unocc}}$= 5.2 (2.5, 10.9)] compared to occupied [$OR_{\text{setbacks, occ}}$= 4.0 (2.1, 7.9)] periods of classroom use, after adjustment for heating/ cooling mechanism (Table 4). For the higher RH cut point (>60%), the effect of setbacks during unoccupied times [$OR_{\text{setbacks, unocc}}$=3.7 (1.7, 8.3)] was slightly weaker but still greater than null compared to classrooms with no setbacks. The association between high RH (>60%) and setbacks was strong but imprecise for occupied times [$OR_{\text{setbacks, occ}}$= 17.5 (2.3, 134)] (Table 4).

Discussion

This study examined the relationship between modifiable, building-related, IAQ factors (mechanical ventilation, maintenance practices, and previous water damage) and longitudinal average daily classroom RH. Classrooms with annual HVAC maintenance had higher odds of having classroom RH >60% [$OR_{\text{annual maintenance}}$=5.8 (2.9, 11.3)], compared to those with quarterly HVAC maintenance. More frequent maintenance may prevent higher humidity by quickly repairing ventilation issues; however, we were limited in our interpretation of this relationship since we were not able to collect longitudinal data on ventilation rates.

Building age was independently related to both HVAC maintenance frequency and classroom RH. Thus, adjustment for building age greatly changed the estimate of the association between HVAC maintenance and RH. The estimate for maintenance performed "as needed," changed both in direction and magnitude after adjustment for building age. (Tables 2–3, and S3, Supp. Materials) Annual maintenance was performed only in 20–45 year-old buildings; whereas, "as needed" maintenance was only performed in 12–38 year-old buildings. All buildings ≤10 years old had quarterly maintenance, which was performed in buildings in each age group. Thus the authors included both adjusted and unadjusted models in the results.

Two unmeasured factors that may have influenced the frequency of school HVAC maintenance were the number and accessibility of units. School maintenance staff in our study reported that proliferation of retrofitted classroom unit ventilators in older schools presented challenges since each unit included many components to maintain. Unit ventilators in the classroom or equipment installed above drop ceilings were difficult to access and involved working at uncomfortable postures and disrupting classroom activities during maintenance. Maintenance personnel reported that more frequent maintenance is easier to perform on centralized HVAC equipment compared to unit ventilators due to the aforementioned challenges, compounded by limited staff and budgets. School districts should consider their ability to meet maintenance requirements when making decisions about which systems to install.

Classrooms in buildings with enthalpy wheels for dehumidification of incoming outdoor air had a higher risk of indoor RH>50%, even after controlling for outdoor humidity, most likely due to the cooling load priority and dehumidification set point of 55% RH. Supporting this theory, the maximum daily mean and 99th percentile RH values were lower for classrooms in buildings with enthalpy wheels (66.2% and 62.5%) compared to without enthalpy wheels (81.9% and 70.5%). When high RH was defined as >60%, classrooms in buildings with enthalpy wheels had a decreased odds [$OR_{enthalpy}$ = 0.58 (0.29, 1.16)] of high RH compared to those without enthalpy wheels (Table S1, Supp. Materials).

The presence of an economizer in the HVAC system was associated with higher odds of having high RH (>60%), after adjustment for the presence of enthalpy wheels for dehumidification (Tables 2 and 3). At first glance, this result suggests that having an economizer, which controls outdoor air dampers to save energy by letting in more outdoor air during mild temperatures and closing dampers during extreme temperatures, may put buildings at risk of having increased humidity. In a humid climate, there is a short window of opportunity for using an economizer when the humidity is low and temperatures are mild. In our study, HVAC units with economizers controlled outdoor air flow based on temperature or schedule, and one unit had the dampers open all the time. None of the HVAC units with economizers had enthalpy wheels for dehumidification of incoming outdoor air. Thus, adjusted estimates should be interpreted with caution, though they showed the same association. Economizer use paired with a desiccant wheel or control of air flow based on outdoor humidity may be better design choices for our climate zone.

All classrooms without programmed setbacks had heat pump/refrigerant HVAC systems. Classrooms in buildings with programmed thermostat setbacks had higher odds of having RH>50% compared to those with no setbacks. Thermostat setbacks are programmed to occur during unoccupied periods of the day, so that the cooling equipment runs less frequently when the heat load is reduced (due to fewer people, less lighting and equipment operating and less solar heat) thus conserving energy and dollars. During the cooling season, the priority is to keep the buildings below a set temperature without regard to the indoor humidity. During unoccupied times in some schools, the amount of outdoor air brought into the building is reduced to a minimum. Even when the incoming outdoor air is reduced through thermostat setbacks, humid outdoor air may be brought into the building during occupied times both intentionally (i.e. custodians may open doors and windows to provide essential ventilation while cleaning) or unintentionally(i.e. leaks from the doors and windows; negative pressure caused by an exhaust fan). In other schools, the air intake fan may operate continuously regardless of whether the cooling mechanism cycles. Under any of these scenarios, when the duration of cooling equipment operation is reduced, the accompanying humidity control is also reduced. In our data, the association between setbacks and high classroom RH >50% was strongest during unoccupied times; however, for high classroom RH>60%, this association was strongest during occupied times. This estimate is unreliable due to many cells where n=0 in the >60% category for some combinations of heating/ cooling mechanism, occupancy, and setbacks.

Other unmeasured factors such as coil temperature, airflow, sensible heat ratio, cycle time, and envelope exchange may affect the ability of HVAC systems to control excessive humidity during the cooling season. However, we did not collect such detailed information on a sufficient number of HVAC units to be able to make such comparisons. Future studies could provide more specific guidance to system designers and operators, by examining the influence of these factors on humidity control.

In classrooms that did not have enthalpy wheels for dehumidification of incoming outdoor air, the humidity was highest during the occupied times and lowest during unoccupied times. One study modeling the impact of maintaining proper ventilation rates on indoor humidity estimated that at 7.1 L/s person without active humidity control, the “space humidity” (g water/ kg of dry air) would frequently be high enough for the air to be fully saturated (Bayer et al., 2002). In our study, district staff hypothesized that certain occupant behaviors may have also contributed increased humidity levels, including turning off unit ventilators (to reduce noise), opening outside windows or doors, and student schedules and activities requiring frequent entering and exiting of the facility. Water vapor from exhalation of occupants may have contributed to higher RH during occupied times.

We did not collect data during the summer months, when most schools were unoccupied for several weeks. One study suggested that absolute humidity may increase during the summer in unoccupied schools without active humidity control (Bayer et al., 2002). Some schools participating in our study ran the boilers during summer months to create an artificial heat load and lower the RH levels. However, we have no data to test this strategy. For future studies, summer (or other extended periods when the schools are unoccupied) may be an important time for capturing this increase in absolute humidity.

Evidence of water damage during the classroom inspection was not associated with high RH >50% and had a slightly protective relationship with high RH >60%. Since the variable was a composite of several variables indicating types of water damage, the authors recoded the analysis variable, removing water damage types less likely be related to current RH (i.e. Water damage from indoor plants, past flooding, etc.). The authors also examined the interaction between water damage and dehumidifier use (Table S6, Supp. Materials). However, the relationship between water damage and high RH moved toward or remained at the null after these changes. Possible reasons for this lack of association include visible water damage being a poor indicator of average RH, misclassification of water damage, and unmeasured occupant behaviors related to visible water damage that would affect RH. We did not collect moisture readings from damaged materials, though such measurements may have been more indicative of the relationship between water damage and high RH. About half (48.9%) of buildings ≤10 years old had visible water damage, indicating that this problem is prevalent in new buildings.

Substantial evidence exists suggesting that indoor dampness increases the risk of respiratory symptoms in building occupants by encouraging microbes to thrive and degrading building materials (Fisk et al., 2010; World Health Organization, 2009). Ramachandran, et al. found that culturable airborne fungal levels in schools increased when indoor RH levels increased (Ramachandran et al., 2005). RH ≥50% may create a hospitable environment for dust mites and was related to an increase in mold spores in one study (Arlian et al., 2002; Jones et al., 2011; World Health Organization, 2009). According to the World Health Organization (WHO), mold growth may appear from 60 to 90% RH, depending on the growth medium, mold species, length of time at high RH and measure of growth (World Health Organization, 2009). Environmental test houses also showed an increase in concentrations of formaldehyde, a known respiratory irritant, which was released from building materials at increased RH levels. In the same study, the largest increases occurred when temperature and RH were simultaneously raised when the indoor climate shifted from heating to cooling (Matthews et al., 1986).

Though indoor dampness is often the primary focus of IAQ improvements, some evidence exists supporting the notion that adverse health effects can occur at both extremes of RH. Low RH can cause drying and irritation of skin and mucous membranes (Reinikainen and Jaakkola, 2003). Dry, irritated mucous membranes may increase human host susceptibility to infection by some viruses; and low RH may increase survival and transmission for some respiratory viruses (Rottem et al., 2002; Shaman and Kohn, 2009; Shaman et al., 2010; Wolkoff and Kjaergaard, 2007). Norback and Nordstrom found decreased odds of fatigue [OR=0.45 (0.20–0.99)] for every 10% increase in RH (Norback and Nordstrom, 2008). Since RH strongly influences human thermal comfort and temperature perception, occupant perception of air quality may be influenced by the discomfort caused by low humidity rather than health effects (Jaakkola et al., 2010). On the other hand, Sundell and Lindvall reported that occupant complaints of "dry air" showed a positive association with condensation on windows and visual signs of water damage (Sundell and Lindvall, 1994). Occupants may confuse symptoms from dry versus humid air, so quantitative RH measurements are essential when addressing complaints.

In our study, some HVAC types reduced humidity to levels low enough to be harmful to human health. Classrooms with a direct expansion (Dx) split system had a higher risk of RH <30% compared to those with a chilled water system. This type of system may provide more dehumidification during its normal processes, with no method of adding moisture to the air if it becomes too dry. As the temperature of air moving across cooling coils is lowered below the dew point, water condenses out of the air stream and onto the coil. Thus, the exiting air stream is at a lower temperature and humidity ratio than the incoming air stream. Cooling to condense water from the air is the latent cooling method of dehumidification, which was the most prevalent dehumidification method among HVAC systems in buildings included in our study. Two new schools had desiccant wheels to remove the humidity from incoming outdoor air; however, the HVAC units with desiccant wheels were not Dx split systems. In addition, enthalpy wheels have the ability to humidify dry incoming outdoor air if necessary, so low humidity was not expected to be a problem in buildings with enthalpy wheels.

Building age was associated with heating/ cooling mechanism. Most buildings ≤10 years old (73.9%) had a chilled water cooling mechanism. The newest school building in our study (less than a year old) had a heat pump with refrigerant cooling HVAC system; whereas, the oldest school building in our study (86 years old) had a Dx split system.

Classrooms in buildings that were between 11 to 40 years old had a higher risk of having RH less than 30% compared to younger buildings, possibly due to the type of HVAC systems in these older buildings. There was no standard set for indoor RH at the lower end of the thermal comfort range in the ANSI/ ASHRAE Standard 55–2004 or related to dehumidification to improve IAQ in the ANSI/ASHRAE Standard 62.1-2007 (ASHRAE 2004; ASHRAE, 2007). Therefore, older HVAC systems may have been designed to dehumidify the school building as much as possible without concern about possible health effects of extremely low humidity. Furthermore, the older facilities lacked temperature sensors in each room, limiting the precision with which the indoor environment could be controlled.

Low RH is associated with adverse health effects; however, the decision to add humidification to an HVAC system should not be made hastily. The health effects from dry indoor air should be weighed against the commitment to maintaining additional equipment and the potential hazards associated with poorly maintained humidifiers, which may support growth of dangerous microbes such as *Legionella sp*. (Hines et al., 2014; Jadhav et al., 2013; Mcconnell et al., 2002; Nordstrom et al., 1994). A comprehensive risk management decision about whether to add humidifiers should weigh school-specific estimates of how many days with low RH may occur during occupied times against the maintenance burden and health effects of humidifiers.

Our study captured longitudinal RH data from a large number of classrooms in buildings with different HVAC types over the course of a school year. Since this was a pilot study, expansion of this research to a larger target population of several school districts may be possible with additional resources to obtain a more representative school sample. Many covariates were collected at the building-level, but introducing building-level random effects severely reduced the precision of the models. Due to the small number of buildings (n=22), some models were not able to converge after we added clustering by building. However, our sample size was large enough to allow us to appropriately cluster the data by classroom.

Collection of additional environmental parameters such as surface moisture levels and air exchange rates may allow us to further clarify relationships between building-related factors and classroom RH.

Conclusion

We suggest actionable areas of improvement for school maintenance including quarterly HVAC maintenance, choice of heating/ cooling mechanisms with respect to humidity control and future maintenance burden of the equipment, adjustment of humidity set points to 50% RH when possible, and careful planning of thermostat setbacks to ensure that humidity control is maintained.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

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Practical Implications

This study combines longitudinal measurements of classroom relative humidity with school inspection data from several schools to describe the problem of relative humidity control in schools. Our findings on how maintenance and mechanical factors affect classroom humidity provide suggestions on building operations policies and heating, ventilation, and air conditioning (HVAC) design considerations that may improve classroom relative humidity control.

TABLE 1

Distributions of NC School Environmental Data, 2010–2011 Academic Year*

			SCHOOL DISTRICT					
			COMBINED		PIEDMONT		COASTAL	
LOCATION	ENVIRONMENTAL MEASURE	N	MEAN (μ)	S.E.	MEAN (μ)	S.E.	MEAN (μ)	S.E.
Indoor**	Relative Humidity (%)	9044 classroom-days	42.7	12.3	43.0	13.5	42.5	11.6
	Temperature (°C)		22.0	1.5	22.0	1.6	21.9	1.3
	Absolute Humidity (g/ m^3)		8.3	2.6	8.4	2.9	8.2	2.4
Outdoor***	Relative Humidity (%)	426 observations‡	69.7	11.6	67.3	13.4	71.0	10.2
	Temperature (°C)		15.3	7.3	13.6	7.8	16.2	6.8
	Absolute Humidity (g/ m^3)		9.9	4.4	8.8	4.4	10.6	4.3

* All data were collected in two phases, from October 20 to December 10, 2010, and from February 6 to June 13, 2011.

** Indoor relative humidity and temperature were recorded every 15 minutes and averaged for each day, by classroom. Missing=22 classroom-days.

*** Outdoor relative humidity and temperature were provided by the NC State Climate Office as daily means of observations collected by the weather station closest to each school, during the data collection periods.

‡ Outdoor measurements were taken from three weather stations during the study follow-up period. Each observation represents one day on which a school near the weather station participated.

TABLE 2

Associations Between Modifiable Building-Related Factors and High Daily Average Relative Humidity Levels (N=9044 Classroom-Days)

		* UNADJUSTED OR (95% CI)		ADJUSTED OR (95% CI)	
		>50% vs 30–50% (ref.)	*>60% vs 30–60% (ref.)*	*>50% vs. 30–50% (ref.)*	*>60% vs. 30–60% (ref.)*
MAINTENANCE					
Water damage[1]	Yes	0.83 (0.54, 1.26)	0.69 (0.39, 1.21)	0.72 (0.47, 1.09)	0.52 (0.28, 0.96)
	No	1.0 (ref.)	1.0 (ref.)	1.0 (ref.)	1.0 (ref.)
Frequency of HVAC maintenance[2]	Annually	1.95 (1.38, 2.8)	4.3 (2.5, 7.4)	6.6 (4.0, 10.8)	5.8 (2.9, 11.3)
	As Needed	0.76 (0.53, 1.08)	1.53 (0.96, 2.4)	4.7 (3.0, 7.4)	4.8 (2.5, 9.2)
	Quarterly	1.0 (ref.)	1.0 (ref.)	1.0 (ref.)	1.0 (ref.)
MECHANICAL-- HEATING, VENTILATION, AND AIR CONDITIONING (HVAC) SYSTEM					
Economizer[3]	Yes	1.14 (0.81, 1.61)	2.5 (1.5, 4.2)	3.1 (2.0, 4.6)	2.6 (1.5, 4.5)
	No	1.0 (ref.)	1.0 (ref.)	1.0 (ref.)	1.0 (ref.)
Heating/ Cooling mechanism[4]	Direct-expansion (Dx) split system	0.06 (0.02, 0.15)	0.08 (0.03, 0.27)	0.03 (0.01, 0.12)	0.06 (0.01, 0.23)
	Heat pump/ refrigerant	1.29 (0.81, 2.1)	0.91 (0.51, 1.62)	1.35 (0.89, 2.0)	0.85 (0.46, 1.55)
	Chilled water	1.0 (ref.)	1.0 (ref.)	1.0 (ref.)	1.0 (ref.)

[*] Estimated generalized logits, clustered by classroom. Total missing n=22 classroom-days. OR=odds ratio, CI=confidence intervals, ref. = referent. Unadjusted ORs measure the univariate associations between each variable and high RH. Adjusted ORs measure the multivariate associations between the main variable and high RH, controlling for potential confounders.

[1] The model for water damage was adjusted for heating/ cooling mechanism, outdoor RH, and building age. Building age was categorized as 0–10, 11–20, 31–40, and >40 years old. No buildings were in the 21–30 age group. Missing "water damage"=289 classroom-days. Water damage included leaks, history of flooding, or visible signs of moisture/ damage.

[2] The model for heating, ventilation, and air conditioning (HVAC) system maintenance frequency was adjusted for building age.

[3] The economizer model was adjusted for use of enthalpy wheels for dehumidification.

[4] The model for heating/ cooling mechanism was adjusted for heating/cooling season and building age. Heating season= outdoor temperature < 15°C, transition= 15–23°C, cooling season= >23°C.

TABLE 3

Associations Between Building-Related Factors and Low Daily Average Relative Humidity Levels (N=9044 Classroom-Days)

		* **UNADJUSTED OR (95% CI)**		**ADJUSTED OR (95% CI)**	
		<30% vs. 30–50% (ref.)	***<30% vs. 30–60% (ref.)***	***<30% vs. 30–50% (ref.)***	***<30% vs. 30–60% (ref.)***
MAINTENANCE					
Water damage[1]	Yes	0.92 (0.61, 1.39)	0.97 (0.60, 1.56)	0.86 (0.57, 1.30)	0.91 (0.59, 1.42)
	No	1.0 (ref.)	1.0 (ref.)	1.0 (ref.)	1.0 (ref.)
Frequency of HVAC maintenance[2]	Annually	0.52 (0.36, 0.77)	0.45 (0.30, 0.65)	0.47 (0.28, 0.78)	0.32 (0.19, 0.54)
	As Needed	1.81 (1.23, 2.7)	2.0 (1.3, 3.2)	1.06 (0.73, 1.53)	0.84 (0.57, 1.25)
	Quarterly	1.0 (ref.)	1.0 (ref.)	1.0 (ref.)	1.0 (ref.)
MECHANICAL-- HEATING, VENTILATION, AND AIR CONDITIONING (HVAC) SYSTEM					
Economizer[3]	Yes	1.21 (0.84, 1.73)	1.23 (0.82, 1.85)	0.84 (0.60, 1.17)	0.65 (0.45, 0.94)
	No	1.0 (ref.)	1.0 (ref.)	1.0 (ref.)	1.0 (ref.)
Heating/ cooling mechanism[4]	Direct-expansion (Dx) split system	2.3 (1.6, 3.3)	3.6 (2.5, 5.2)	2.46 (1.6, 3.8)	2.7 (1.7, 4.4)
	Heat pump/ refrigerant	1.40 (0.82, 2.4)	1.23 (0.70, 2.2)	0.97 (0.49, 1.94)	0.93 (0.47, 1.82)
	Chilled water	1.0 (ref.)	1.0 (ref.)	1.0 (ref.)	1.0 (ref.)

[*] Estimated generalized logits, clustered by classroom. Total missing n=22 classroom-days. OR=odds ratio, CI=confidence intervals, ref. = referent. Unadjusted ORs measure the association between each building-related factor and low RH. Adjusted ORs measure the association between the building factor and low RH, using a multivariate model controlling for potential confounders.

[1] The model for water damage was adjusted for heating/ cooling mechanism, outdoor RH, and building age. Building age was categorized as 0–10, 11–20, 31–40, and >40 years old. No buildings were in the 21–30 age group in this study. Missing "water damage"=289 classroom-days. Water damage included leaks, history of flooding, or visible signs of classroom moisture/ damage.

[2] The model for heating, ventilation, and air conditioning (HVAC) system maintenance frequency was adjusted for building age.

[3] The model for HVAC system economizer was adjusted for use of enthalpy wheels for dehumidification.

[4] The model for heating/ cooling mechanism was adjusted for heating/cooling season and building age. Heating season= outdoor temperature < 15°C, transition= 15–23°C, cooling season= outdoor temperature >23 °C.

TABLE 4

Effects of Thermostat Setbacks on Average Relative Humidity Level, Stratified by Building Occupancy (N= 14952 Classroom Observations) *

		** Adjusted OR (95% CI)			
Thermostat setbacks	**Building Occupied**	***Low Relative Humidity***		***High Relative Humidity***	
		>30% vs 30–50% (ref.)	***>30% vs 30–60% (ref.)***	***>50% vs 30–50% (ref.)***	***>60% vs 30–60% (ref.)***
Yes vs. No	Un-stratified	0.84 (0.30, 2.4)	0.55 (0.18, 1.63)	4.3 (2.3, 7.9)	7.0 (2.6, 19.4)
	Yes	0.79 (0.26, 2.4)	0.52 (0.17, 1.61)	4.0 (2.1, 7.9)	17.5 (2.3, 133.9)
	No	1.10 (0.41, 3.0)	0.67 (0.23, 1.94)	5.2 (2.5, 10.9)	3.7 (1.65, 8.3)

* For each combination of classroom and day, relative humidity (RH) observations were averaged separately for times when the buildings were occupied versus unoccupied. Average classroom RH, stratified by occupancy, was then categorized using the cut points listed in this table.

** Estimated generalized logits clustered by classroom, using different RH cut points. Odds ratios are adjusted for heating/ cooling mechanism. Missing n=22 classroom-days. OR=odds ratio, CI=confidence intervals, ref. = referent.